Spin orientation and spin currents induced by linearly polarized light

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To date, optical orientation of free-carrier spins and spin currents have been achieved by circularly polarized light, while the linearly polarized light has been used for optical alignment of electron momenta. Here we show that, in low-dimensional structures, absorption of the linearly polarized light also leads to the spin polarization and spin photocurrent, and, thus, the electron and hole spins can be manipulated by light of zero helicity. The microscopic description of the both effects is developed for interband optical transitions in undoped quantum wells (QWs) as well as for direct intersubband and indirect intrasubband (Drude-like) transitions in n-doped QW structures.

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I. PURE SPIN PHOTOCURRENTS

Pure spin current represents a non-equilibrium distribution where free carriers, electrons or holes, with the spin "up" propagate mainly in one direction and equal number of spin-down carriers propagates in the opposite direction. This state is characterized by zero charge current because electric currents contributed by spin-up and spin-down quasiparticles cancel each other, but leads to accumulation of the opposite spins at the opposite edges of the sample. Spin currents in semiconductors can be driven by an electric field acting on unpolarized free carriers (the so-called spin Hall effect). They can be induced as well by optical means under interband or intraband optical transitions in non-centrosymmetrical bulk and low-dimensional semiconductors [1, 2, 3, 4].

The appearance of a pure spin current in semiconductor quantum wells (QWs) under interband optical pumping with linearly polarized light is linked with the spin splitting of the energy spectrum, which is linear in the wave vector $\mathbf{k}$, and the spin-sensitive selection rules for the optical transitions. The effect is most easily conceivable for direct transitions between the heavy-hole valence subband $hh1$ and conduction subband $e1$ in QWs of the C_s point symmetry, e.g., in (110)-grown QWs. In such structures the spin component along the QW normal $z' \| [110]$ is coupled with the in-plane electron wave vector. This leads to $\mathbf{k}$-linear spin-orbit splitting of the energy spectrum as sketched in Fig. 1, where the heavy hole subband $hh1$ is split into two spin branches $\pm 3/2$. In the reduced-symmetry structures, the spin splitting of the conduction subband is usually smaller than that of the valence band and not shown for simplicity. Due to the selection rules the allowed direct optical transitions from the valence subband $hh1$ to the conduction subband $e1$ are $|+3/2\rangle \to |+1/2\rangle$ and $|-3/2\rangle \to |-1/2\rangle$, as illustrated in Fig. 1 by vertical lines. In the presence of the spin splitting, electrons with the spins $\pm 1/2$ are photoexcited in the opposite points of the $\mathbf{k}$ space which results in a flow of electrons within each spin branch. The corresponding fluxes $\mathbf{j}_{+1/2}$ and $\mathbf{j}_{-1/2}$ are of equal strengths but of opposite directions. Thus, this non-equilibrium electron distribution is characterized by the nonzero spin current $\mathbf{j}_{\rm spin} = (1/2)(\mathbf{j}_{+1/2} - \mathbf{j}_{-1/2})$ but a vanishing charge current, $e(\mathbf{j}_{+1/2} + \mathbf{j}_{-1/2}) = 0$.

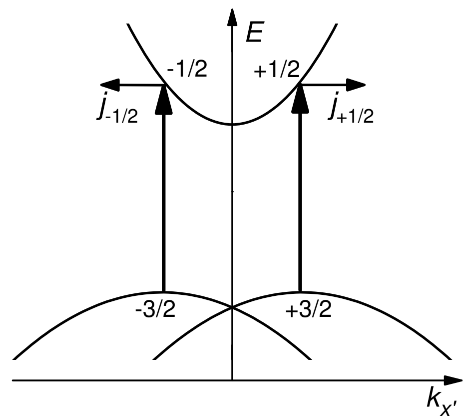

FIG. 1: Microscopic origin of pure spin photocurrent caused by spin splitting of the band structure.

In general, the flux of electron spins can be characterized by a pseudo-tensor $\mathbf{J}$ with the components J_β^α describing the flow in the β direction of spins oriented along α, with α and β being the Cartesian coordinates. The non-zero components of the photo-induced spin current are determined by the light polarization and the explicit form of spin-orbit interaction. The latter is governed by the QW symmetry and can be varied. In (110)-grown QWs the absorption of unpolarized light leads to a flow along $x' \parallel [1\bar{1}0]$ of spins oriented along z'. This component can be estimated as

$$J_{x'}^{z'} = \gamma_{z'x'}^{(hh1)} \frac{\tau_e}{2\hbar} \frac{m_h}{m_e + m_h} \frac{\eta_{cv}}{\hbar\omega} I \,, \qquad (1)$$

where $\gamma_{z'x'}^{(hh1)}$ is a constant describing the $\mathbf{k}$-linear spin-

orbit splitting of the $hh1$ subband, τ_e is the relaxation time of the spin current, m_e and m_h are the electron and hole effective masses in the QW plane, respectively, η_{cv} is the light absorbance, and I is the light intensity.

Another contribution to spin photocurrents may come from **k**-linear terms in the matrix elements of the interband optical transitions. Taking into account $\mathbf{k}\cdot\mathbf{p}$ admixture of the remote condution band Γ_{15} to the valence-band and conduction-band states $X_\mathbf{k}, Y_\mathbf{k}, Z_\mathbf{k}$ and $iS_\mathbf{k}$, one derives the interband matrix elements of the velocity operator for bulk zinc-blende-lattice semiconductors [5]

$$\begin{aligned} \langle iS_\mathbf{k}|\mathbf{e}\cdot\mathbf{v}|X_\mathbf{k}\rangle &= (P/\hbar)[e_x + i\beta(e_y k_z + e_z k_y)]\,, \\ \langle iS_\mathbf{k}|\mathbf{e}\cdot\mathbf{v}|Y_\mathbf{k}\rangle &= (P/\hbar)[e_y + i\beta(e_x k_z + e_z k_x)]\,, \\ \langle iS_\mathbf{k}|\mathbf{e}\cdot\mathbf{v}|Z_\mathbf{k}\rangle &= (P/\hbar)[e_z + i\beta(e_x k_y + e_y k_x)]\,, \end{aligned} \quad (2)$$

where $\beta = QP'(2E'_g + E_g)/[PE'_g(E'_g + E_g)]$ is a material parameter, P, P' and Q are the interband matrix elements of the momentum operator at the Γ point multiplied by $\hbar/m_0$ (m_0 is the free electron mass), E_g and E'_g are the energy band gaps, and $x\|[100]$, $y\|[010]$, $z\|[001]$. For GaAs band parameters [6] the coefficient β can be estimated as 0.2 Å. Calculation shows that, in (110)-grown QWs, the spin photocurrent caused by **k**-linear terms in the interband matrix elements has the form

$$J_{x'}^{z'} = \beta\varepsilon(e_{y'}^2 - e_{x'}^2)\frac{\tau_e}{\hbar}\frac{\eta_{cv}}{\hbar\omega}I\,, \quad J_{y'}^{z'} = \beta\varepsilon e_{x'}e_{y'}\frac{\tau_e}{\hbar}\frac{\eta_{cv}}{\hbar\omega}I\,, \quad (3)$$

where $\varepsilon = (\hbar\omega - E_g)m_h/(m_e + m_h)$ is the kinetic energy of the photoexcited electrons, $\mathbf{e} = (e_{x'}, e_{y'}, 0)$ is the light polarization vector, $y'\|[00\bar{1}]$. In contrast to Eq. (1), this contribution depends on the polarization plane of the incident light and vanishes for unpolarized light. The spatial separation of opposite spins, which depends on the light polarization, has been observed in Ref. [3]. However, estimations show that the contributions (1) and (3) in GaAs-based QWs are comparable in magnitude for the excitation with 100 meV above the band edge.

In (001)-grown QWs the absorption of linearly- or unpolarized light results in a in-plane flow of electron spins. In contrast to the low-symmetry QWs considered above, in (001)-QWs the linear-in-**k** terms in the matrix elements of optical transitions under normal incidence vanish, and the spin photocurrents are entirely related to the spin-orbit splitting of the free-carrier subbands.

Intrasubband optical transitions. Light absorption by free carriers, or the Drude-like absorption, is accompanied by electron scattering by acoustic or optical phonons, static defects etc. Scattering-assisted photoexcitation with unpolarized light also gives rise to a pure spin current [2, 4]. However, in contrast to the direct transitions considered above, the spin splitting of the energy spectrum leads to no essential contribution to the spin current induced by free-carrier absorption. The more important contribution comes from asymmetry of the electron spin-dependent scattering.

II. OPTICAL ORIENTATION BY LIGHT OF ZERO HELICITY

Optical excitation with linearly polarized light in QWs can also result in the spin orientation of photoexcited carriers. This effect is related to the reduced symmetry of QW structures as compared to bulk crystals and forbidden in bulk cubic semiconductors. Theory of the optical orientation by linearly polarized light has been developed in Refs. [7, 8] for the direct interband and indirect intrasubband transitions. Microscopically, the effect is a two-stage process involving (i) asymmetrical spin-dependent photoexcitation of the carriers followed by (ii) spin precession in an effective magnetic field induced by the Rashba or Dresselhaus spin-orbit coupling. Direction of the average spin is determined by the structure symmetry and geometry of photoexcitation. In (001)-grown QWs, the linearly-polarized normal-incidence excitation results in the spin orientation along the QW normal, with the spin sign and magnitude depending on the orientation of light polarization plane. Estimations show that the spin orientation by linearly polarized light can reach a few percents and is experimentally accessible.

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